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THE IMPACT OF THE SOLAR CYCLE ON OVER-THE-HORIZON RADAR SYSTEMS

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INTRODUCTION

Skywave Over-the-horizon Backscatter radar systems (OTH-B RS) depend on ionospheric propagation conditions. These change with many different cycles; the diurnal cycle, the seasonal cycle and the solar cycle; and with the geographic location and design of the system. Testing the radars under conditions that represent the range of possible variations is difficult. An operational test of a half year or less, can obtain representative data for all but the solar cycle. Missing geographic ionospheric test conditions can be obtained by using data gathered in other locations and by using historical data. Testing system performance over the solar cycle can be accomplished by modeling and simulation. Several models have been developed to accomplish this task. The drawback to this approach is that modeling requires forecasts for the next solar cycle which the scientific community has great difficulty providing.

This paper reviews the impact of solar cycle ionospheric changes have on OTH-B RS that operate in the mid-latitude ionosphere, and view the polar and the equatorial ionosphere. These effects are related to the solar cycle changes in solar flux and geomagnetic conditions. The lack of success of the solar-terrestrial physics community in forecasting the next solar cycle and the accompanying geomagnetic disturbances is considered. Finally, an approach to circumvent the need for a forecast of the solar flux magnitude and timing in OTH-B RS performance modeling is suggested.

THE IONOSPHERE

The Earth's ionosphere is primarily created by electromagnetic radiation from the sun. Because of atmospheric chemistry and density, different altitudes are affected by different frequencies of radiation. Figure 1 shows the number of free electrons that are created by this radiation during solar minimum and maximum. The OTH-B RS depends on the electron density, the height of the ionosphere and the take off angle of the radar beam to determine the radar range that ionospheric refraction can support. As the numbers of electrons increases with the solar cycle the OTH-B RS operators have an easier time finding frequencies to reach the desired range. At solar minimum, reaching the longer radar ranges is difficult. During solar maximum the D-region also is stronger causing increased absorption of the lower frequency energy during the day time. The increase in daytime absorption is not nearly as great as the increase of available frequencies, providing a wider band of available frequencies at solar maximum. (Ivanov-Kholodny & Mikhailov, 1986)

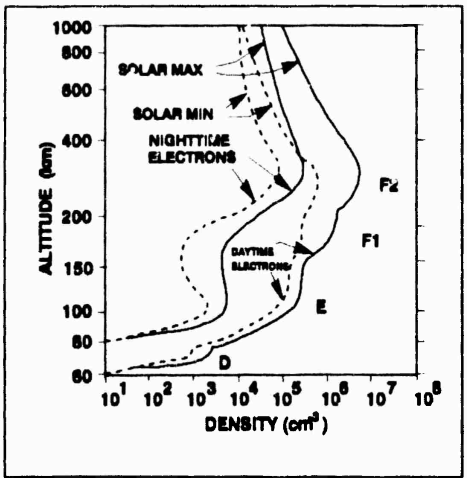

Figure 1. Electron density of the different layers of the ionosphere at solar maximum and minimum.

The increase in available frequencies at solar maximum is not all good. Other users of the HF spectrum also have much improved propagation conditions, as does naturally generated HF noise. The result is that OTH-B RS can "hear" more noise at solar maximum decreasing the signal to noise ratio and increasing the probability that there may be

fewer available channels during solar maximum because of the non-interference requirement of the U.S. OTH-B RS.

GEOMAGNETIC DISTURBANCES

The degree of disturbance in the Earth's magnetic field also affects the way the ionosphere is able to support operating frequencies. Figure 2 shows the impact of a geomagnetic disturbance at mid-latitudes. Note that strong geomagnetic field variations will restrict substantially the available frequencies particularly during the critical sunrise transition period. (Townsend et. al., 1982)

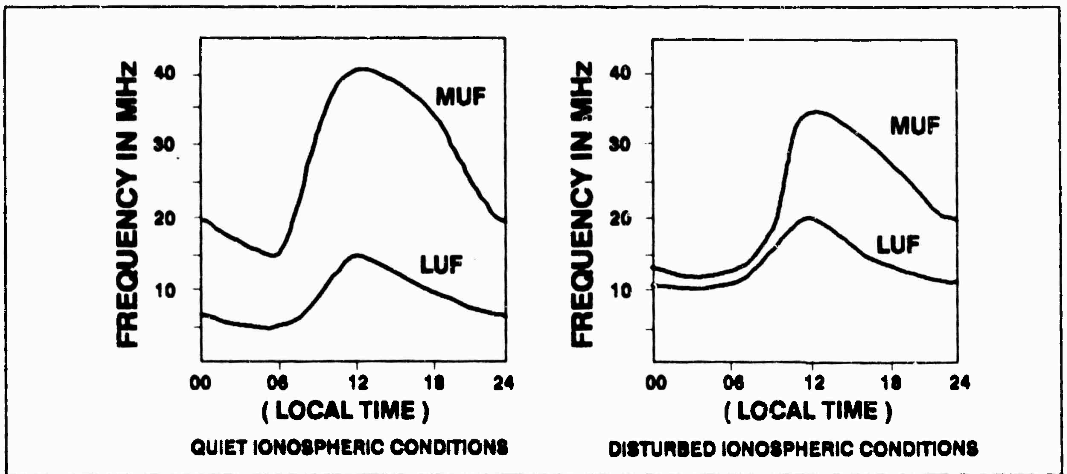

Figure 2. Available frequencies during a disturbed geomagnetic field period at solar maximum and solar minimum on a mid-latitude communications circuit.

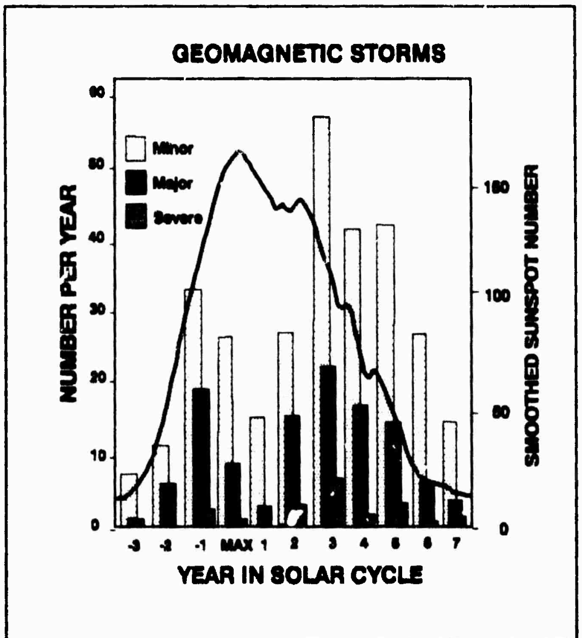

Figure 3. The occurrence of geomagnetic disturbances through out the solar cycle.

These Geomagnetic disturbances tend to occur on the down side of the solar cycle as shown in figure 3. The events of 1989, however, show that a few geomagnetic disturbances of record size can occur on the rising side, figure 4. At solar maximum, large and frequent geomagnetic disturbances generally result from solar activity. The position of the Earth in relation to the solar position of the event controls how strong the resulting geomagnetic disturbance will be.

The occurrence and strength of geomagnetic disturbance control the location of the auroral zone with regard to the ionospheric reflection points. As the level of disturbance increases the auroral zone moves south. OTH-B RS have difficulty operating in this zone, because of absorption and noise. Geomagnetic disturbances pushed the auroral zone down as far as the middle of Air Force OTH-B East Coast (ECRS) and Alaskan radar systems coverage during the first part of 1989. Figure 5 shows the southerly penetration of the auroral zone into the OTH-B ECRS coverage. This figure is based on the Q index (Feldstein, 1967) and is derived from the visible aurora.

Geomagnetic disturbances have three critical effects on the coverage of the OTH-B RS. First, as the aurora zone moves south any sectors with ionospheric refraction points in or near the zone will have reduced frequency availability and in general will be unavailable. The exception is when aurcral sporadic-E supports coverage. This occurs consistently only on north looking paths during strong events. Second, to the south of the auroral zone the available frequencies will be restricted with increased noise. In addition, the number of clear- free channels will decrease due to competition with other users who are also affected. Under these conditions multipath tracks will increase as will azimuthal location errors. The latter is the result of electron density tilts along mid-latitude paths. Finally, when geomagnetic activity is low OTH-B RS looking into equatorial zones will experience increased noise as a result of equatorial disturbances.

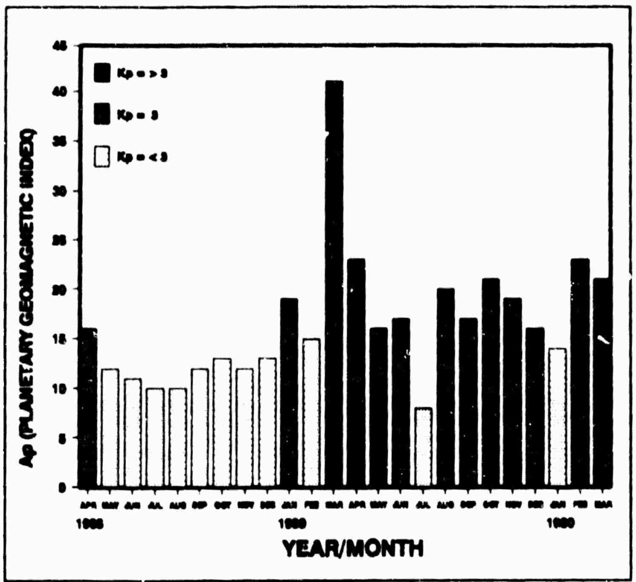

Figure 4. The level of geomagnetic disturbance during 1988-1989 as measured by the Air Force (SESC) A_p geomagnetic index.

EPISODIC DISTURBANCES

Many short term geophysical effects have dramatic effects on OTH-B RS. The occurrence of these effects are also solar cycle related. Major effects are sudden ionospheric disturbances (SID), sporadic E (E_s), Spread-F, Equatorial noise and Travelling Ionospheric Disturbances (TID). (Trizna & Headrick, 1981)

The most dramatic episodic event is the solar flare. Solar flares were originally observed as very bright optical events on the surface of the sun. While dramatic, the important aspect of these events to the OTH-B RS is their X-ray output, which raises the lowest usable frequency on the sunlit paths. This sudden ionospheric disturbance (SID) ensures that at the peak of a large flare, the lowest usable frequency is above the HF band. These peaks last for a few minutes to an hour. Figure 6 shows the relationship of the of solar flare occurrence to the solar cycle while figure 7 shows the relationship of X-ray events to the solar cycle. While the occurrence of optical flares track the solar cycle the large X-ray flares clearly reach a maximum on the down side of the cycle.

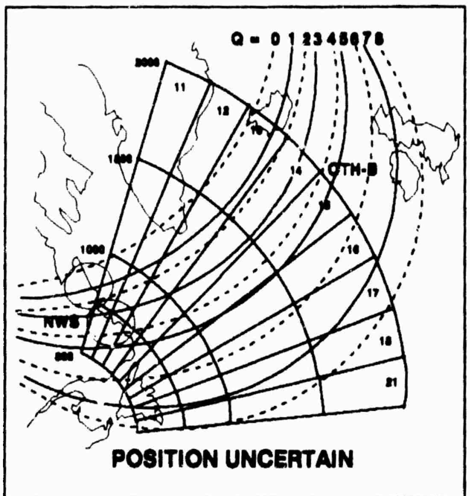

Figure 5. The position of the auroral zone for different levels of geomagnetic disturbances indicated by the index Q. The position for the higher numbers are uncertain.

Sporadic E is a dense layer of electrons in the E-region between 100-120 km, which does not seem to be related to normal E-region layers. E_s is a serious problem for OTH-B RS because the strength, location, and time of occurrence change rapidly. In addition, the virtual height of the layer is independent of frequency and can be partially penetrated by the beam. E_s may cover so small a area that only a part of the beam is reflected. The net effect of E_s is to increase clutter and intermittently provide real targets at the wrong ranges. E_s occurrence follows different rules in mid-latitudes than it does in auroral latitudes.

Auroral E_s is related to the occurrence of geomagnetic disturbances and therefor the solar cycle. Mid-latitude E_s is less associated with the solar cycle, as the operating frequencies rise the impact of mid-latitude E_s on OTH-B RS decreases.

Spread-F is an ionospheric phenomena that manifests itself on vertical ionosondes as energy returned from many altitudes and frequencies, rather than the altitude band that normally refracts radar energy at a given frequency. On OTH-B radar mid-latitude paths, this phenomena is observed as increased noise because the radar energy is reaching the ocean, and any target, by many paths. When spread-F is occurring these radars are generating there own noise. Some spread-F also creates an increase in Doppler spread.

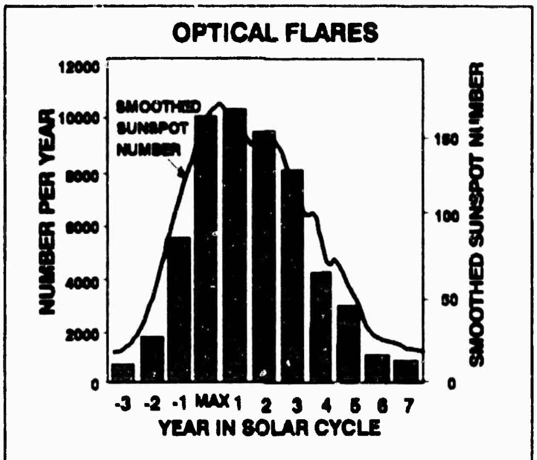

Figure 6. The occurrence of solar flares viewed in the optical band during the solar cycle versus the sun spot number.

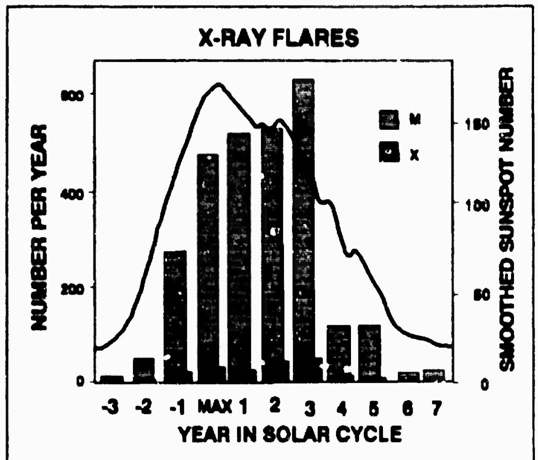

Figure 7. The occurrence of X-ray flares during the solar cycle versus the sun spot number.

In the mid-latitudes, Spread-F tends to decrease with increasing sun spot numbers, and is not very strong at any time. At equatorial latitudes spread-F increases with increasing solar flux, but decreases with disturbances in the geomagnetic field. Strong Spread-F in the equatorial zones is maximum in the hours after local sunset. At solar maximum the increase in the propagating range of the Air Force OTH-B ECRS reaches the equatorial zones. At this time the Spread-F becomes a strong self generated noise source. This manifestation of equitorial noise is observed on the oblique ionosondes as diffuse energy returns at 4000-5000 miles. It is probable this effect will be noted on other OTH-B RS viewing the equatorial regions.

Traveling ionospheric disturbances (TIDs) result from gravity waves in the upper atmosphere. As these waves move past an ionospheric reflection point the electron density decreases and then increases at the reflection height causing radar range errors with a duration of tens of minutes. Electron density changes on the order of a dwell period and spreading of the Doppler from the Earth's surface and any targets will cause a significant increase in Doppler signal noise.

TIDs occur more frequently at solar maximum and virtually all TIDs with large changes in electron density occur at solar maximum. TIDs have been noted on the Jindalee OTH-B Radar. (Anderson and Lees, 1987) The significance of this effect for OTH-B RS is that this noise source frequently occurs on mid-latitude paths during solar maximum and is often overlooked by the operator.

IMPLICATIONS FOR TESTING OTH-B RADAR SYSTEMS

The changes in continuous and episodic ionospheric events with 11 year solar cycle variations in solar flux and geomagnetic activities pose serious problems for operational OTH-B RS testing. Clearly if a reasonable test period is used it is impossible to test an OTH-B radar in the variety of ionospheric conditions that are expected over the life of the system. Testing under these conditions is necessary because of the demonstrated importance of the

ionosphere to OTH-B RS. The solution is to use an ionospheric model that can simulate the radar performance under the un-testable conditions. Several of these models have been developed (Elkins, 1988 and Szuszczewicz, 1988). The major problem with the models is that they both require an input of solar flux and geomagnetic activity index, and the quality of long term forecasting of these parameters is not good.

SOLAR CYCLE FORECASTING

The forecasting of the critical solar and geomagnetic indices has been improving during the latest solar cycle, but have a long way to go before forecasts within 10% of the actual magnitude of the solar maximum are realized. Figures 8 and 9 show the distribution of collected forecasts for solar cycles 21 and 22 with the cycle 21 maximum and the current cycle 22 observation for comparison. (Brown 1984) Figure 9 also contains forecasts that post date the Meudon workshop, from which the basic figure was taken. No forecast of solar cycle 23 were offered at the 1989 Solar Terrestrial Predictions Workshop.

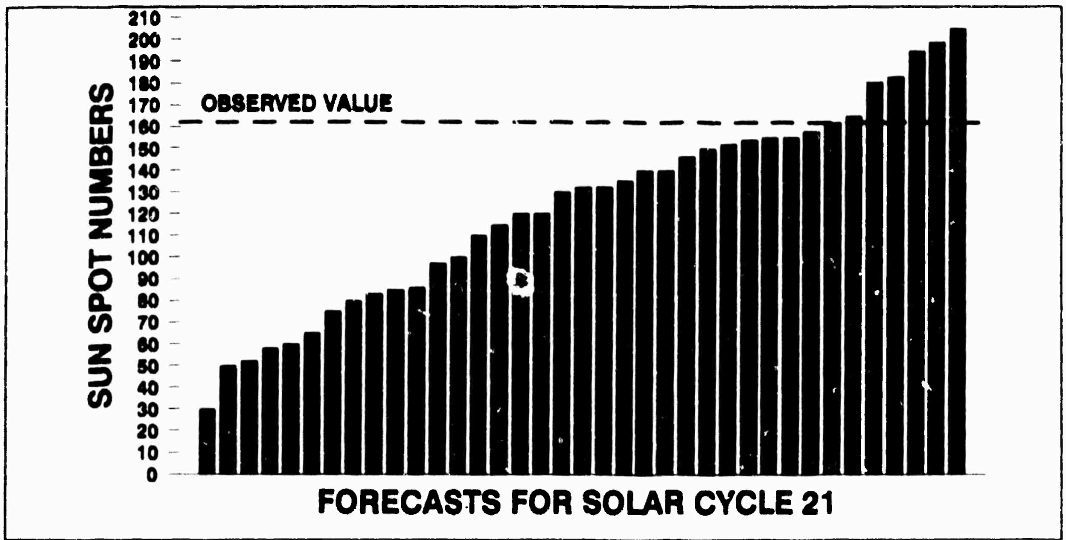

Figure 8. Thirty eight forecasts for solar cycle 21 sun spot maximum compared to the observed maximum.

These two figures represent forecasts made prior to or in the first few months of 1984. A dynamo theory prediction for Solar Cycle 22 (Schatten, 1984) was provided at the same meeting, and is presented in figure 10. This prediction for the declining sun spot number of solar cycle 21 and the forecast for cycle 22, is updated using a current Space Environmental Laboratory forecast. (SEL, 1990) The monthly average observations to date are included for comparison.

GEOMAGNETIC DISTURBANCE FORECASTING

Geomagnetic disturbances are also hard to forecast over the solar cycle. These disturbances are separated into two categories, sudden commencement and gradually commencing disturbances. Sudden commencements storms are related to the shock waves associated with solar flares. On the average stronger solar flares result in stronger geomagnetic disturbance events. The correlation between sun spot numbers and this type of geomagnetic disturbance is .85. (Mayaud, 1975)

Gradually commencing geomagnetic disturbances tend to reoccur with the 27 day rotation period of the sun. These events are the result of interaction between the solar wind and the geomagnetic field. The events can be very strong and comprise the bulk of all geomagnetic disturbances. Gradual commencement disturbances reach a maximum during the declining portion of the sun spot cycle. There appears to be a slow increase in the number and magnitude of the gradual commencing disturbances. Substantial errors occur in the prediction these

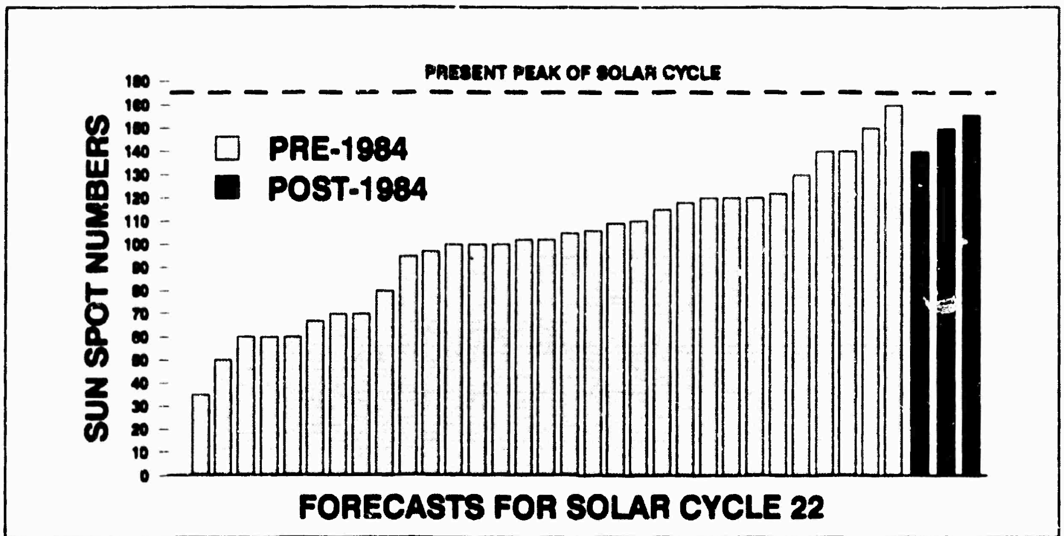

Figure 9. Forecast of sun spot numbers for solar cycle 22 using the dynamo theory of prediction, with the current smoothed monthly value. The first 31 were presented at the Meudon Workshop while the last three were made in 1984, 1985 and 1987 respectively.

disturbances over a solar cycle. Climatological geomagnetic disturbance forecasting is considerably less certain than sun spot forecasting as shown by the data for 1980 when a smoothed yearly sun spot number of 154 would normally indicate strong disturbances. This year, however, was one of the quietest geomagnetic periods on record. (Feynman and Gu, 1986) This dip in geomagnetic indices also occurred during several earlier cycles.

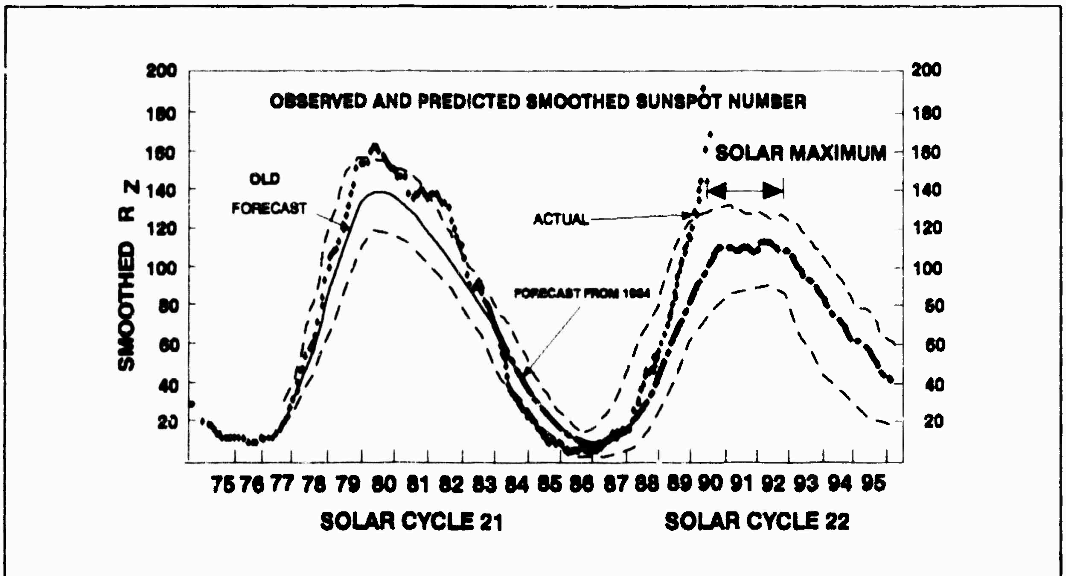

Figure 10. Sun spot forecasts for solar cycles 21 and 22 using the dynamo technique. The actual observations and the 20% confidence limits are also provided.

The forecast of the frequency of occurrence of geomagnetic disturbances in general show a bimodal distribution. The first peak is near solar maximum and is dominated by the sudden commencement disturbances associated with flares. The second peak occurs well into the declining phase and is dominated by the gradual commencement, reoccurring storms. The larger

peak appears to alternate with the odd numbered cycles the peak near solar maximum is larger. The reverse appears true for even numbered cycles. (Hedeman and Dodson-Prince 1984) The leveling off of the observed increase in the number of disturbances during the last two solar cycles lead to a predicted decrease in the number of disturbances in cycle 22. This certainly is not true to date.

FORECASTING SOLAR FLUX VALUES FOR OTH-B RADAR SYSTEM TESTING

This paper has demonstrated both that testing OTH-B radar systems requires consideration of the solar cycle and that forecasting this cycle is very difficult. An alternative approach takes a statistical view of the solar flux values during a solar cycle and applies Monte Carlo techniques to determine which flux values to use for a particular run of the model. This approach has the advantage that no forecast of the next solar cycle flux peak and timing is required. Any error in the peak value of the flux for cycle 23 will be minimized by the relatively short duration of these high numbers. Figure 11 shows a frequency distribution derived from the daily sunspot values from the last five solar cycles. The choice of five cycles is derived from the recognition that solar cycles in this half of the century have been increasing in strength, indicating a distribution containing many lower values are not desired. A number of recent papers that show the long term history of solar activity is similar to the 400 years of recorded data support this conservative approach (Withbroe, 1989)

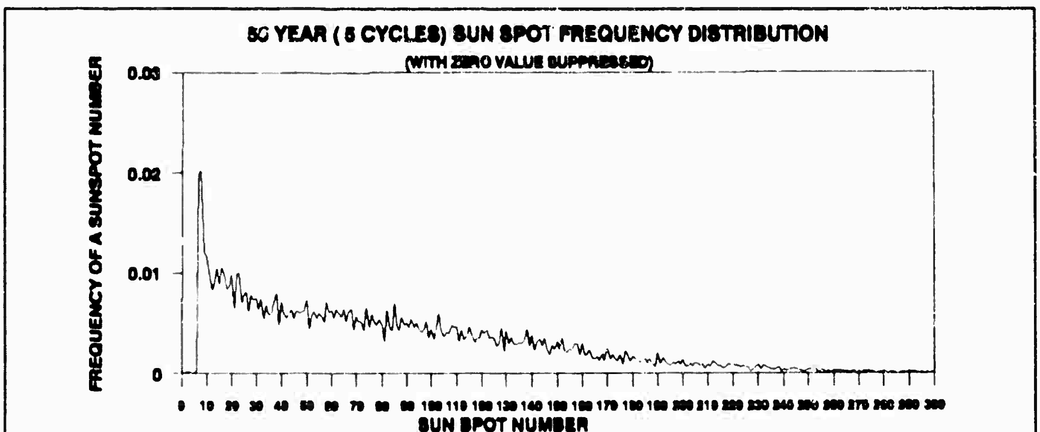

Figure 11. The frequency of occurrence of sun spot numbers during a solar cycle. These values were computed from the last five solar cycles. Sun Spot number zero has a frequency of 6%.

SUMMARY

This paper has shown that ionospheric variation is a critical factor in the operation of OTH-B RS. The range of flux values over the solar cycle causes great variation in the ionosphere. Ionospheric modeling is required for the testing of an OTH-B RS. The major problem in applying these models lies in forecasting the solar cycle. The paper recommends a sun spot frequency of occurrence distribution as a solution to this problem and provides one suggested distribution.

REFERENCES

Anderson S. J. and M.L. Lees, 1987; " High-Resolution Synoptic Scale Measurements of Ionospheric Motions with the Jindalee Radar" in The Effect of the Ionosphere on Communication, Navigation, and Surveillance Systems, ed Goodman, Naval Research Lab, p169-176.

Brown, G.N. 1984; Working Group "A" Report: Long Term Solar Predictions, Solar-Terrestrial Predictions Workshop at Meudon, FR; pp1-7.

Elkins, T.J. 1988; OTH Radar Performance Estimation, MITRE Working Paper, WP-27739.

Feldstein, Y.I. and G.V. Starkov, 1967; "Dynamics of Auroral Belt and Polar Geomagnetic Disturbances," Planet. Space Sci., 15, p209.

Feynman and Gu, 1986; Prediction of Geomagnetic Activity on the Scale of One to Ten Years, Rev. Geophy., 24, 3, pp 650-666.

Hedeman and Dodson-Prince, 1984; Indications of Probable Levels of Sunspot Numbers and Geomagnetic Disturbances in Solar Cycle 22, Solar-Terrestrial Predictions Workshop at Meudon, FR; pp97-98.

Ivanov-Kholdny, G.S. and A. V. Mikhailov, 1986; The Prediction of Ionospheric Conditions, D. Reidel Pub. Co., Boston, pp95-97.

Mayaud, P.N.,1975; Analysis of Storm Sudden Commencement for the Years 1868-1967, JGR, 80, 111.

Schatten, 1984; Solar-Terrestrial Predictions Workshop at Meudon, FR; Jun 84, pp92-96.

Space Environmental Laboratory, 1990 ; Preliminary Report and Forecast of Solar Geophysical Data. U.S. Department of Commerce.

Szuszczewicz, 1988; OTH-B-PROP; A COMPUTER MODEL FOR THE TEST AND EVALUATION OF OTH-B PROPAGATION CHARACTERISTICS IN THE GLOBAL-SCALE IONOSPHERE, a briefing to The Air Force Operational Test and Evaluation Center, 9 August 1988, SAIC, McLean, VA 22102.

Townsend,R. E., R. W. Cannata, R. D. Prochaska, G.E. Rattray, and J.C. Holbrook; 1981, Source Book of Solar-Geophysical Environment, AFGWC/TN-82/002

Trizna, D. B. and J. M. Headrick, 1981, "Ionospheric Effects HF Over-the-horizon Radar", in Effects of the Ionosphere on Radio Wave Systems, ed. Goodman, Naval Research Laboratory, pp262-272.

Withbroe, 1989, Solar Activity Cycle: History and Predictions, J. Spacecraft and Rockets, v26#6, pp.394-402.